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ULTRAVIOLET DISINFECTION OF DOMESTIC SEWAGE AND STORMWATER

– a literature evaluation

Research Paper # 2046

December 1978

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Ontario Ministry of the Environment

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ULTRAVIOLET DISINFECTION

OF DOMESTIC SEWAGE AND STORMWATER

- a literature evaluation

Research Paper #2046

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December, 1978

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NOTICE

Mention of trade names or products is for purposes of illustration and does not imply endorsement or recommendation for use by the Ministry of the Environment.

1. ULTRAVIOLET RADIATION FOR DISINFECTION

1.1 Introduction

Terminal disinfection of wastewater is conventionally carried out using chlorine. Within the last few years, problems and dilemmas have arisen in the use of chlorine (1) which have prompted a search for alternatives. Alternatives with comparable costs and equivalent or better disinfecting ability have been favoured. A prime requirement for any alternative is that it avoids the problems associated with chlorine without causing new problems to arise.

Ultraviolet radiation (UV) has been reported (2,3,4,5,6) as having considerable potential for wastewater disinfection and likely to prove problem-free in use. However, relatively little material has been published on UV which is specific to wastewater disinfection. A large part of the following report is drawn from publications relating to the UV disinfection of drinking water which has received much more attention. Detailed accounts of UV disinfection have been published by Jagger (6) and Loufbourow (7).

1.2 Purpose and Ontario Experience

A literature search was undertaken to summarize the present state-of-the-art in the use of UV radiation to disinfect wastewater from water pollution control plants, combined sewer overflows and storm sewers. This report is based on the results of the literature search. The work was done as part of a Canada/Ontario Agreement (C/OA) research project investigating alternative methods of treating storm-water runoff from separate sewered areas (C/OA 76-8-37).

A few studies of UV disinfection have been carried out in Ontario. Oliver et al (2,3) at the Canada Centre for Inland Waters and Gurak and Hargrave (8) at the University of Toronto studied disinfection of domestic wastewater. Vajdic (9) and Oda (10) of the former Ontario Water Resources Commission (now Ontario Ministry of the Environment) studied the UV disinfection of potable water. No references were located in the literature on UV disinfection of stormwater or combined sewer overflows.

1.3 Historical Background

The germicidal effects of UV radiation have been known for many years. One of the earliest discoveries relating to the bactericidal effects of radiant energy was made by Downes and Blunt in 1878 (11). They observed the effect of sunlight on a mixed population of microorganisms and concluded that radiation of short wavelength (UV) was responsible for microbial destruction.

In 1901, Hewitt invented a mercury vapour lamp which is the prototype of the UV lamps used today. In 1906, it was determined that enclosing a lamp in a quartz sheath would minimize the adverse effects of low ambient temperatures on the efficiency of UV emission. Quartz sheaths are widely used in commercial equipment today.

Prior to 1920, UV disinfection of water supplies was the subject of much interest, but the equipment had poor reliability and was difficult to maintain. Chlorine proved to be more reliable and more economical. Additionally, and in contrast with UV, the chlorine

added for disinfection could also maintain a distribution system residual. However, development of UV technology continued and was utilized in the food and bottling industries for both air and process water treatment.

More recently, UV has been used for water disinfection for shipboard use and increasingly for the disinfection of private water supplies. Development work carried out by the manufacturers to obtain the approval of regulatory agencies has resulted in some further advances in technology, particularly in the area of radiation-detectors which respond specifically to UV wavelengths.

1.4 Principles of UV Disinfection

Light is a form of energy which can be absorbed by chemical compounds. The absorption of light (photons) results either in structural changes within the chemical, or emission of the absorbed energy without any structural change. The changes and emissions are primarily an electron-excitation phenomenon (6).

A specific chemical compound can only absorb certain wavelengths of incident radiation. Different effects can therefore be produced by different wavelengths. The UV wavelengths are around 2537 Å, and are absorbed by chemical compounds with conjugated structures (alternating single and double bonds between carbon atoms). Exposure of microorganisms to ultraviolet light results in structural changes of their deoxyribonucleic acid (DNA) and their ribonucleic acid (RNA).

The changes in DNA are significant because DNA controls the reproduction of the organism. The resultant alteration of DNA, does not kill the microorganism but prevents propagation. Therefore, when the treated organism dies naturally, a new generation is not produced and the water has been disinfected (12).

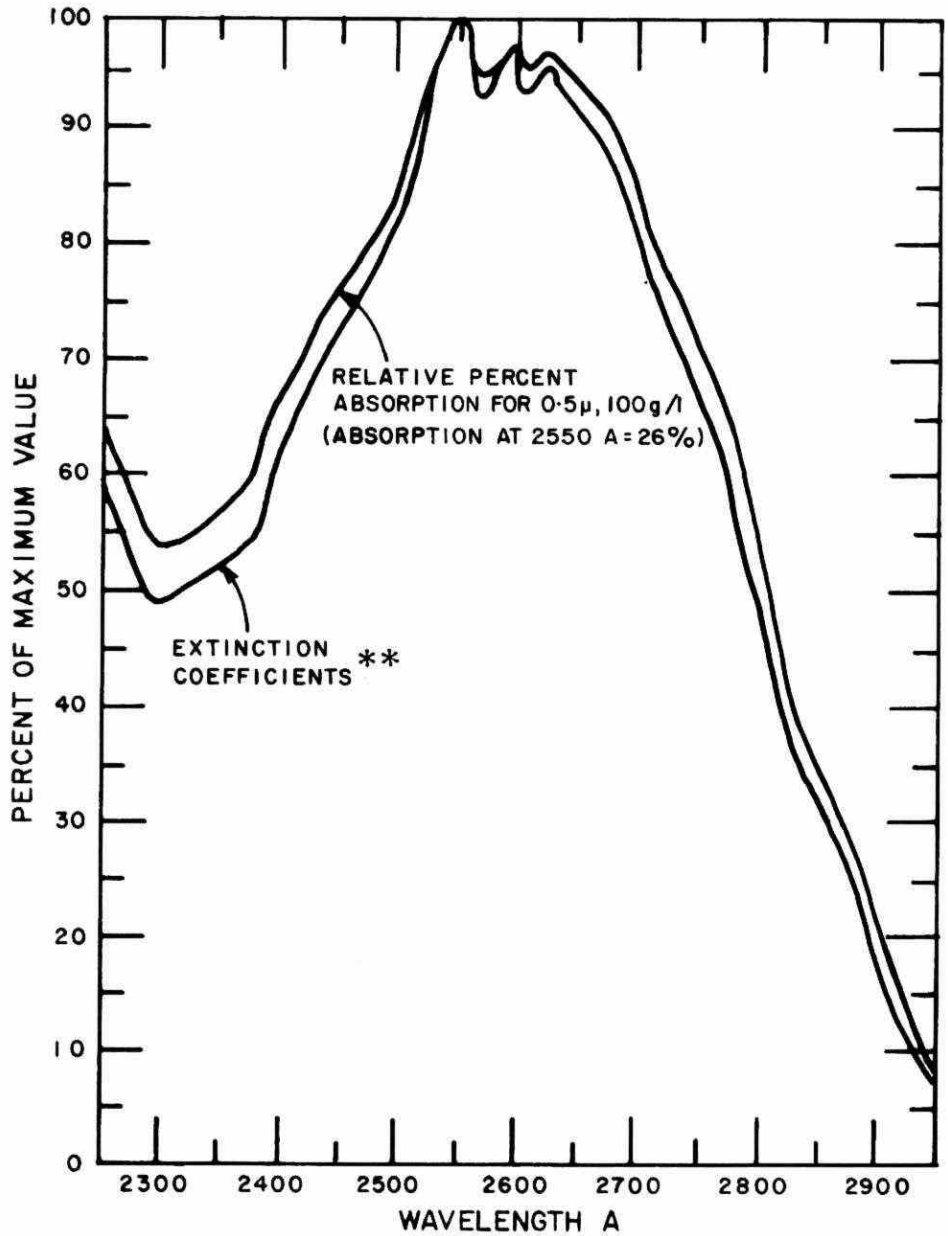
Figure 1 (upper line) is a plot of the relative absorption of energy from radiation of different wavelengths by a suspension of RNA particles. Absorption at 2550 Å is used as the reference point for relative absorption. The lower line of the figure illustrates the relative spectral effectiveness of the same range of wavelengths in inhibiting colony formation of E.coli bacteria.

The figure shows that there is a close correlation between the two effects. RNA is chemically similar to DNA; hence, their response to radiation should be similar. The figure supports the idea that disinfection results from the structural changes induced in the DNA by the UV radiation.

There is indirect evidence that pyrimidines, especially thymine, are the major class of compounds affected by the UV radiation during inactivation of microorganisms (6).

UV absorption by inorganic compounds is rarely of significance above 2000 Å. Further, single bond or saturated organic compounds rarely enter into UV induced reactions when the radiation is above 2200 Å (6). Since most mercury lamp emissions are above 2200 Å, inorganic, single bond compounds or saturated organic compounds would rarely be affected by the UV radiations from mercury lamps used for disinfection.

Water itself is very transparent to ultraviolet light; consequently, Loofbourow (7) does not expect water to be directly affected by UV radiation. Jagger (6), however, thinks that there is a possibility that water may enter into chemical reactions with those chemicals altered



* ABIOTIC IS THE ADJECTIVAL FORM OF ABIOSIS – THE ABSENCE OF LIFE

** A MEASURE OF THE INHIBITING EFFECT ON BACTERIAL COLONY FORMATION

FIGURE 1: RELATIVE ABIOTIC EFFECT OF ULTRAVIOLET ON E.COLI COMPARED WITH RELATIVE ABSORPTION OF RIBOSE NUCLEIC ACID (7)

by the UV light. Chemical changes caused by UV could occur in the DNA of microorganisms or in any other conjugated-bond compound present in the water. UV absorption by chemical compounds will not only decrease the UV energy available for disinfection, but could result in chemical micro-contamination of the product water (13).

Variation in the germicidal efficiency of UV radiation relative to efficiency at 2600 Å is illustrated in Figure 2. The germicidal effect is indicated as greatest between 2500 Å and 2700 Å which is typical of most microorganisms. There is an abrupt decrease of effectiveness from 2700 Å to 3000 Å and from 2500 Å to 2100 Å. A continual decrease of effectiveness would be shown if the graph were extended into visible light wavelengths of 4000 Å to 7000 Å (11).

The actual dosage of UV radiation required to achieve a given level of bacterial inactivation is highly dependent on the conditions of disinfection.

In relation to germicidal effectiveness, it is also known that microorganisms can repair themselves under specific natural conditions. Dosage-inactivation relationships and factors affecting UV disinfection efficiency and organism self-repair are discussed in later sections.

1.5 Exposure and Safety Considerations

When compared with other means of disinfection, UV should prove exceptionally safe to use in practice; the radiation is generated and used on-site, has relatively mild physiological effects and can be easily confined within the equipment used.

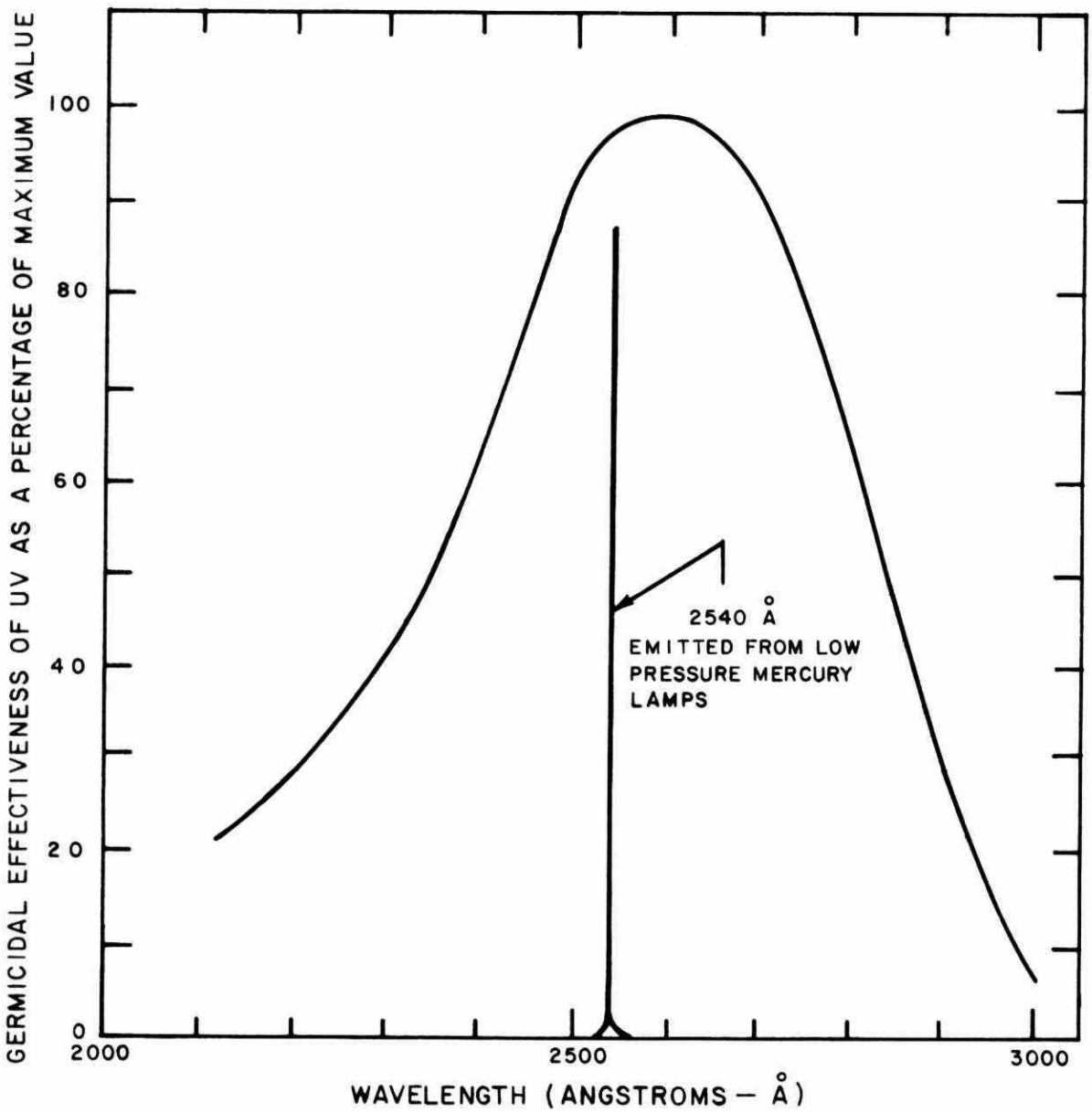


FIGURE 2: RELATIVE GERMICIDAL EFFECTIVENESS OF RADIANT ENERGY (10)

With prolonged or intense human exposure, UV radiation may cause painful irritation to the eyes and reddening of the skin. Personal protection can be obtained by using eyeglasses or clothing since neither can be penetrated by UV radiation. Westinghouse, a supplier of UV lamps, notes in a general information booklet (14), that accepted practice is to have a maximum human exposure of 0.5 microwatts per square centimeter for eight hours, decreasing to 0.1 mw/cm^2 for 24 hours exposure. The booklet also states that, apart from the effects noted above, "there are no known harmful physiological effects from ultraviolet radiation".

Operators responsible for the operation of UV equipment should probably be encouraged to wear the appropriate protective equipment - especially eyeglasses - at all times as a basic preventive safety measure.

1.6 Toxicity of UV Disinfected Wastewaters to Aquatic Life

UV disinfection is used as part of the treatment process for feedwater in many marine laboratories, fish hatcheries, shellfish cultivation facilities and the like. The Ministry of the Environment uses it as a stage in water treatment for preparing water used for bioassays in its Rexdale aquatic toxicity laboratory (15).

The lack of toxicity of high quality UV irradiated waters is well known and induced toxicity in UV disinfected wastewaters would be unexpected. However, comparatively few data are available. Continuous 96-hour, on-line bioassays of secondary sewage effluents

were carried out using rainbow trout as the test organism in a study at Brampton, Ontario (2). No mortality occurred in undisinfected or UV disinfected effluent while a parallel bioassay on chlorinated effluent resulted in mortalities.

1.7 Ultraviolet Disinfection vs Chlorine Disinfection

Chlorine is used extensively and almost exclusively in North America for the disinfection of Water Pollution Control Plant (WPCP) effluents. Chlorine is also the prime candidate for the terminal disinfection of treated urban runoff. It is already being used for full-scale disinfection of combined sewer overflow at a few locations.

Current Ontario practice for disinfection of WPCP effluent requires an end-of-contact residual of 0.5 mg/L chlorine. Chlorine is toxic to fresh water organisms - levels of as little as 0.002 mg/L are required to avoid adverse effects on cold water fish (16). To avoid chlorine toxicity in the receiving stream, effluent dechlorination is being considered in some Ontario locations. At such locations, the cost and relative merits of UV disinfection should be compared with those of chlorination-dechlorination rather than with chlorine disinfection alone.

Chlorine disinfection has also been cited (16) as producing organic byproducts which may represent a long term health hazard to humans.

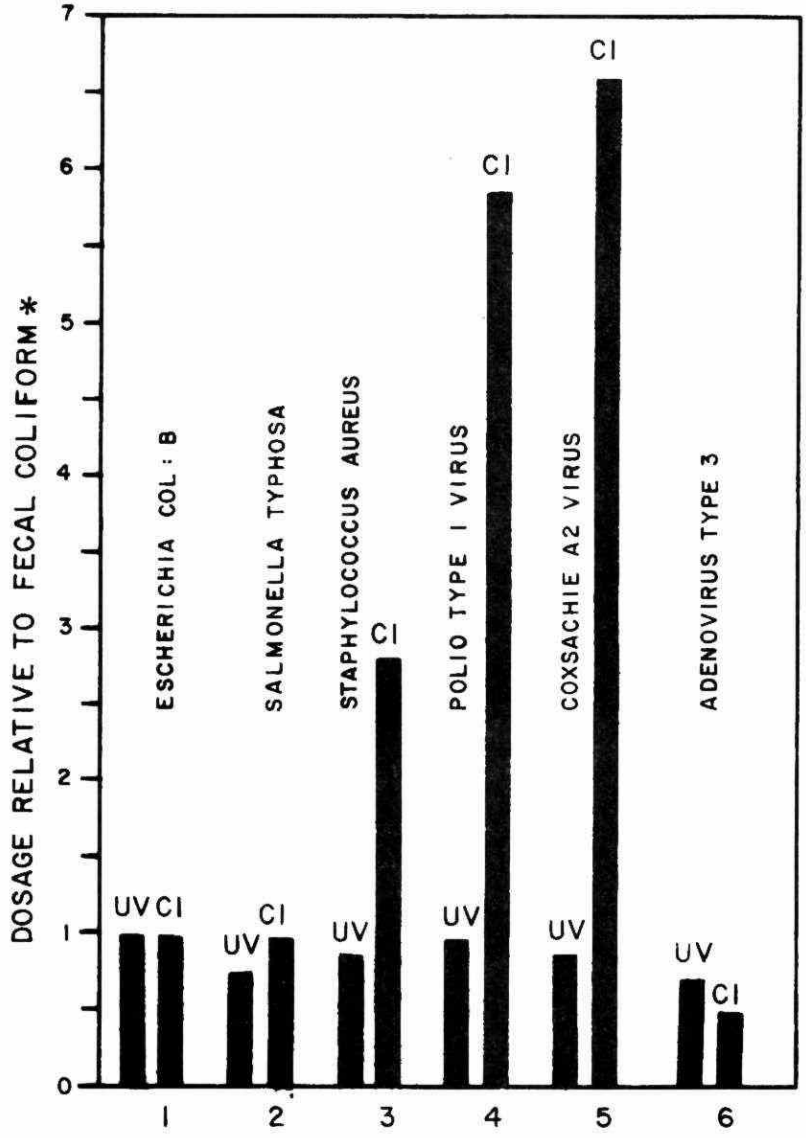
No 'residual' results from UV disinfection, therefore, toxic effects on aquatic organisms are unlikely. The likelihood of producing significant amounts of harmful chemical byproducts also appears to be low although definitive proof is lacking.

Various types of microorganisms have different susceptibilities to the germicidal action of a specific disinfectant; relative susceptibility also changes for different disinfectants. Figure 3 (2) compares the UV dosages required to inactivate some common pathogenic bacteria and viruses relative to the dosage required for inactivation of fecal coliforms. The figure also presents comparable data for chlorine and it can be seen that some of the bacteria and viruses are much less sensitive to chlorine than are fecal coliforms. By contrast, all the pathogens and viruses shown are as sensitive, or more so, to UV light than fecal coliforms. Thus, if sufficient UV light to kill 99% of the bacteria (indicator bacteria) is supplied, at least 99% of these pathogens and viruses should be destroyed (2).

Colour and turbidity at moderate levels have minimal effect on bacterial kill by chlorine (2). However, the levels of colour and turbidity are critical factors in determining the efficiency of UV disinfection (6).

Electricity consumption projected for UV disinfection is 3-4 times that for chlorination of secondary effluent - even with full allowance for the electricity used in manufacture of the chlorine (16, 17).

A comparison of the costs for chlorination and UV disinfection of municipal secondary wastewater is presented in Section 4 - Cost of Disinfection.



*A ratio of one indicates that the bacteria or virus has the same susceptibility to the disinfectant as fecal coliform. A ratio greater than I indicates less susceptibility.

FIGURE 3 : MORALITIES OF INDICATOR BACTERIA AND PATHOGENS (2)

2. FACTORS AFFECTING THE EFFECTIVENESS OF THE ULTRAVIOLET DISINFECTION OF WASTEWATERS

Kills of more than 99% have been obtained for total coliforms, fecal coliforms, fecal streptococci and heterotrophic bacteria by irradiating secondary effluent from conventional activated sludge sewage treatment plants with UV light (3). Some of the physical factors which can affect the efficiency of UV disinfection of bacteria are discussed below.

2.1 Intensity and Dosage

Tests have been made to determine if intensity (mw/cm^2) or dosage ($mw\ sec/cm^2$) of UV light influences the efficiency of bacterial inactivation (3). Luckiesh and Holliday (18) investigated inactivation of several hundred cultures of *E.coli* and presented the following equation:

$$\frac{N}{No} = e^{-\frac{Et}{Q}}$$

Where: N - is the average number of surviving organisms

No - is the number before irradiation

E - is the intensity of germicidal energy

t - is the time of exposure in minutes

Q - is the exposure (Et), termed a unit lethal exposure - 40 $mw\text{-}minutes/cm^2$ for *E.coli*

Based on equations such as that above, it is now generally accepted that bacterial kill depends primarily on dosage and not intensity. It therefore follows, that as the intensity decreases, the exposure or treatment time must increase proportionally to produce the same efficiency of inactivation. This is generally true until time becomes so large that other independent kinetic factors would alter the life cycle of the micro-organisms. Therefore, time of exposure should be short in relation to life

of the organisms being studied. During the logarithmic growth stage of bacteria, a typical life expectancy would be 20 to 30 minutes. In water and wastewater disinfection, the dosage is usually applied in a period of less than a minute.

Units of UV dosage are usually expressed as Einsteins or watt-seconds. The conversion from one unit to the other can be obtained from the fundamental equation:

$$E = h \frac{c}{\lambda}$$

where: E = energy at a specific wavelength (ergs)

h = Planck's constant

c = speed of light (cm/sec)

λ = wavelength of light (cm)

Therefore: $$E_{2540\text{Å}} = \frac{6.6256 \times 10^{-27} \times 2.9999 \times 10^{10} \text{ cm/sec}}{2.54 \times 10^{5} \text{ cm}}$$

$$= 7.82 \times 10^{-12} \text{ ergs}$$

since 1 erg = 6.024×10^{16} joule/mole

$$E_{2540\text{Å}} = 7.82 \times 10^{-12} \times 6.024 \times 10^{16}$$

$$= 47.1 \times 10^{4} \text{ joule/mole}$$

since 1 joule = 1 watt-sec

and 1 mole = 1 einstein

$$E_{2540\text{Å}} = 47.1 \times 10^{4} \frac{\text{watt-sec}}{\text{mole}}$$

or 1 einstein = 47.1×10^{4} watt-sec.

With respect to the required precision of dosage, Jagger (6) indicates that "absolute dose-rate measurements to an accuracy of ±10% may be considered excellent for most biological work, and even errors as high as 50% may be tolerated (but are not desirable) since the measurement of effect is seldom better than ±10% and the absolute values reported by different workers may vary greatly because of different physical setups or biological conditions". (Equipment for measuring dosage is discussed in Section 3.4).

The intensity of UV emissions from mercury vapour lamps can be affected by changes in lamp temperature and supply voltage, which in turn can alter the total dosage of UV received by organisms and hence disinfection efficiency. (Characteristics of ultraviolet equipment are discussed in Section 3).

Typical dosage values required to inactivate 90 or 100% of various microorganisms are presented in Table 1 (3). The data illustrate the different sensitivities of various types of microorganisms to UV light. The table also shows that E. coli requires a lower dosage for 90% inactivation than some of the common pathogens, viruses and E.Coli bacteriophage.

UV equipment suppliers are able to state the minimum UV intensity available for treatment within their unit. Combining such data with research results similar to that in Table 1, produces a first or minimum estimate of the exposure time required for a given level of inactivation of specific microorganisms.

TABLE 1

DOSAGE REQUIRED TO INACTIVATE VARIOUS MICROORGANISMS (3)

Total Dosage Microwatt Secs. per cm^2	Organism
400,000	Algae, Blue-green*
200,000	Paramecium
90,000	Penicillium digitatum
40,000	Nematode eggs*
15,000	S. typhimurium
10,000	Pseudomonas aeruginosa
9,000	Clostridium tetani
8,000	Bacillus anthracis Neisseria catarrhalis
7,000	Escherichia coli Salmonella typhosa
6,500	Cholera
6,000	Bacteriophage (E.coli) Corynebacterium diphtheriae Infectious Jaundice Poliomyelitis
5,000	Streptococcus Hemolyticus
4,000	Streptococcus pyogenes Dysentery bacilli Typhoid
3,000	Streptococcus viridans Influenza

* Indicates 90% kill as opposed to 100% for other organisms.

In practice, commercially available equipment for water disinfection applications incorporates various safety factors in design which result in increased contact time. For disinfection of wastewater or urban runoff, safety factors are not well-defined - site specific pilot plant testing seems desirable in the present state-of-the-art.

2.2 Photoreactivation

Photoreactivation is the process whereby the UV altered DNA of a microorganism is repaired by enzymatic reaction. The activating material is radiation of wavelengths in the near UV and the lower end of visible light (3000 Å to 5000 Å). Therefore, reactivating wavelengths are present in sunlight. The most effective wavelength depends upon the type of organisms (6).

Photoreactivation is enhanced if a UV irradiated bacterial cell is expossed under appropriate environmental conditions to high intensity black light (around 3650 Å). As a result, the organism can continue to grow and propagate thus negating the disinfecting effect of the UV light. "Dark" repair may also occur if the organisms are retained in a "no growth" condition (without light, and with minimal nutrients). In this case, there may be time for other enzymes to repair the DNA (12), and the disinfecting effect will be negated when the organism again reaches conditions appropriate for growth.

To date, photoreactivation has been found to apply only to bacteria and not to viruses or enzymes. But a virus can be reactivated if absorbed into a host. Recovery is then dependent on host metabolism (20). Whether repairs of bacteria, viruses and enzymes would occur to a significant extent in receiving waters is unknown.

After inactivation, the disinfected material will contain viable and non-viable cells. After exposure to a reactivating environment, the population will consist of the viable cells, photoreactivated cells and the inactivated cells (21). Some of the photoreactivated cells may be mutants of the originals depending on whether the repair reproduces the original DNA structure or recombines the DNA into a new but viable form. One author also found that photoreactivation of E.coli "was proportional to the time of exposure times the intensity of reactivating light, and the effect increased with a rise in temperature" (21). This author also stated that in his experiments to induce photoreactivation he obtained a 60% removal of the lethal effects of the UV. Reactivation was studied under favourable conditions where the cells were kept in an incubation chamber in the dark and without nutrient addition. Even so, reactivation was only possible if commenced within 3 hours of inactivation.

Another factor to be considered in photoreactivation is the possibility of an increased rate of cell division of those cells still viable after irradiation. Increases may occur due to the larger volume of liquid per living cell and also because there is less competition for food and nutrients (7). A further consideration is that the residuals from dead cells may stimulate growth of undamaged cells.

2.3 Mutation

Mutation of irradiated cells is possible when UV alters the DNA or RNA of bacteria to another viable state, such that descendents have different characteristics from those of the pre-irradiated cell. Conditions are most favourable for mutation when the total dose applied is not such as to kill a large fraction of treated cells (22). UV

is not unique in causing mutation; other forms of radiation, and many chemical substances, can also induce mutation rates under favourable conditions (22). Mutation also occurs spontaneously during normal reproduction, hence, the effect of irradiation is to increase the rate of mutation. Shortly after irradiation, the mutation rate returns to the spontaneous rate. Mutants become active either within minutes of inactivation or after one or two divisions. The first condition occurs less frequently than the latter (21).

Mutation in pure cultures is detected by differences of morphology growth substrate, antibiotic sensitivity, virus susceptibility, etc. (6). Deciding whether mutations are caused by the UV light will be very difficult, considering the multiplicity of microorganisms present in wastewater or urban runoff.

2.4 Effect of Wastewater Quality

The efficiency of inactivation depends on the effective dosage applied. With decreased transmission, the depth of flow that can be effectively treated is reduced by the need to maintain a minimum lethal dosage at maximum working depth. The transmission or conversely the absorbence of UV light per unit depth to liquid is therefore very important. It can also vary greatly. For example, 90% of incident UV energy is absorbed in 3 meters of distilled water while the same amount may be absorbed in 12 cms of drinking water.

One common way of describing the absorption characteristics of water is to measure the depth at which 90% of the applied UV energy is absorbed, the "effective depth of penetration". Another way is to determine the coefficient of absorption (α) in the expression:

$$\alpha = \frac{Lnt}{d}$$

where Lnt = natural logarithm of percent transmission

d = liquid depth in centimeters

The above equation can be rearranged to show that for a fixed coefficient of absorption, transmission varies exponentially with liquid depth.

The two major factors affecting absorption and transmission are suspended solids and dissolved organics. The former block the light penetration, whereas the latter can absorb the energy.

Table 2 illustrates the effect of wastewater depth on the dosage required for equivalent disinfection efficiency (2). As the depth of secondary effluent increases from 0.5 cm to 3 cm, the dosage of radiation required for a 99% kill of fecal streptococcus increases by a factor of eighteen. This indicates that in wastewater disinfection, equipment should be used which limits the depth of flow to a few centimeters at most.

TABLE 2

COMPARISON OF UV DOSAGE REQUIRED AT DIFFERENT DEPTHS OF FLOW FOR A 99% INACTIVATION OF FECAL STREPTOCOCCUS (2)

Depth of Flow (cms)	Source of Secondary Effluent	Dose* mw sec/cm
0.5	-	14,300
1.0	Oakville (east)	35,200
	Oakville (main)	37,400
	Clarkson	44,000
3.0	Hamilton	231,000
	Brampton	251,000
	Burlington	257,000

*Reference quotes dosage as w sec/Imp. gallon. This has been converted by putting reference data in the formula:

$$\frac{\text{Reference Dosage} \times 10^6 \text{ (mw/w)}}{\frac{4546 \text{ (cm}^3\text{/gal)}}{\text{Depth of flow (cm)}}}$$

In addition to changes in the physical/chemical quality of the wastewater, changes in the bacterial densities in the undisinfected wastewater can also be expected to affect the total dosage of UV radiation required for effective disinfection. Initial bacterial levels can vary widely. For example, raw sewage can have 10^{12} total coliforms per 100 ml, secondary effluent may have 10^5/100 ml, while combined sewer overflows and stormwater may have 10^7 and 10^4/100 mls respectively (23, 24).

Figure 4 (3) illustrates the effect of changes in wastewater quality on the UV dosage required for equivalent disinfection efficiency. The improvements in quality achieved by secondary treatment greatly increased the efficiency of bacterial inactivation for a specific UV dosage. In raw sewage, the surviving fraction of bacteria levels off

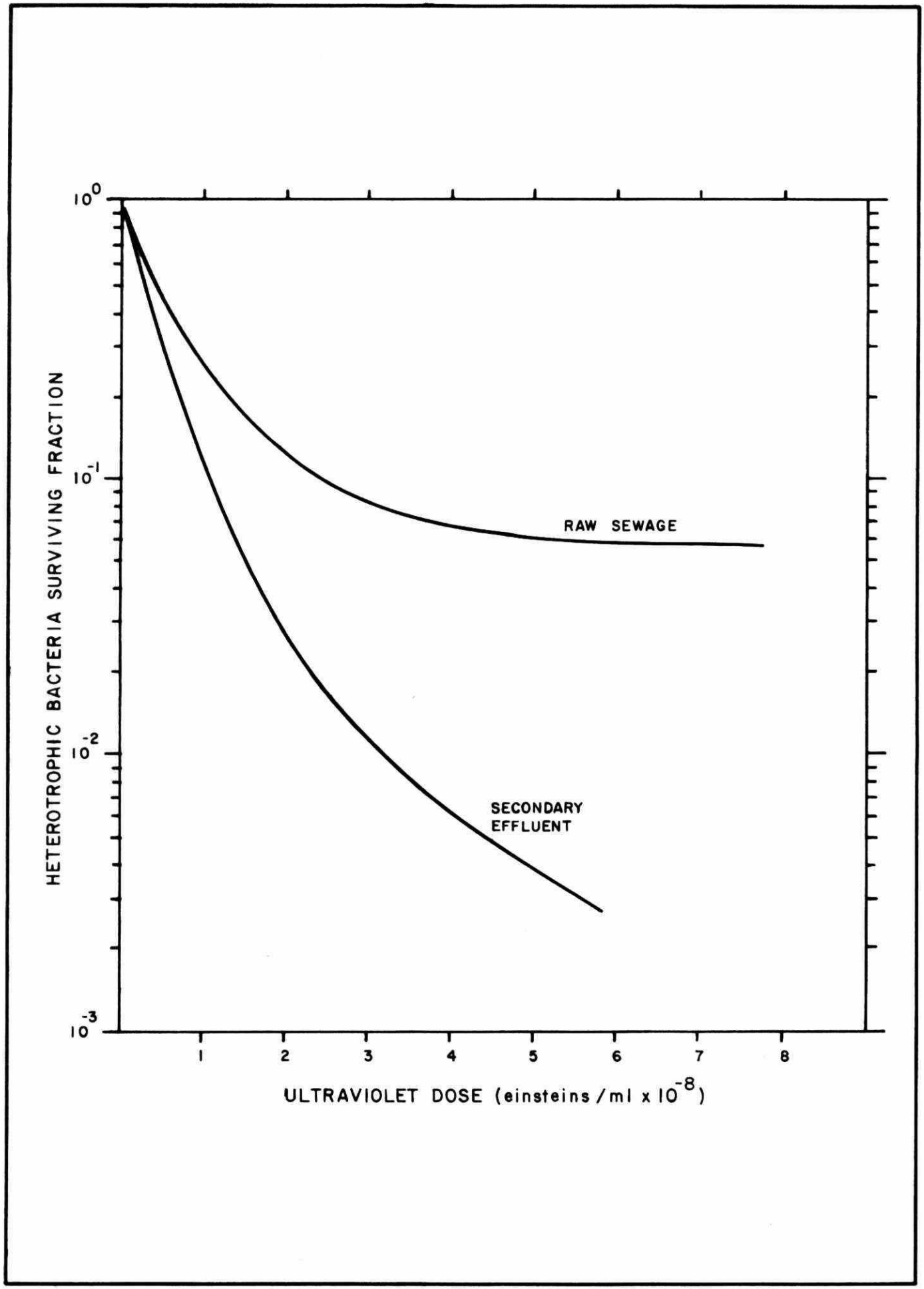


FIGURE 4 : COMPARISON OF THE DISINFECTION OF RAW DOMESTIC SEWAGE AND SECONDARY TREATMENT PLANT EFFLUENT *(3)*

at about 0.065, which indicates that there is a limiting inactivation level at which higher dosages of UV light will not improve disinfection efficiency.

As a further example of the effect of improved wastewater quality on UV disinfection, it was noted in a study at Dallas, Texas (13) that UV penetration increased with degree of nitrification in the sewage treatment process. This was thought to occur because nitrified effluent contained lower levels of dissolved organic compounds when compared with conventional secondary effluent. Soluble organic compounds capable of absorbing UV light (12) include those with groupings such as:

$C = C-C = C$

- aromatic rings
- Flavinoids
- Acridines

Many of the absorbing compounds, including humic substances are coloured and for this reason, it may be advisable to monitor colour in wastewater disinfection applications. However, colour units are unreliable as a primary indication of likely UV absorption as illustrated by Table 3. Four colouring agents were added to separate samples of bacterially contaminated water. The samples were then disinfected by UV light. Methylene blue produced the highest colour, best UV transmission and least adverse effect on bacterial inactivation.

Soluble iron salts in water or wastewater are changed to an insoluble form by UV radiation. This increases wastewater turbidity and deposits precipitates directly onto immersed lamps or their quartz sheaths. Such deposits reduce the UV transmission.

TABLE 3

EFFECT OF COLOUR ON ULTRAVIOLET INTENSITY

AND TREATMENT EFFICIENCY (25)

Colouring Agent and Organism	Colour Units*	UV Meter Reading	Influent Count (per 100 ml)	Effluent Count (per 100 ml)
Methylene blue:				
E. coli	33	16	2,100,000	< 0.067
A. aerogenes	30	15	210,000	< 0.067
	15	20	3,400,000	< 0.067
S. faecalis	33	16	4,600,000	< 0.067
Orzan S:				
E. coli	15	2	40,000	150.0
	7	7	3,400,000	< 0.067
	5	11	1,900,000	< 0.067
A. aerogenes	7	7-8	630,000	< 0.17
S. faecalis	7	7	18,000,000	0.13
	5	11	9,600,000	0.067
Tea				
E. coli	12	5	4,000,000	330.0
	7	9	1,400,000	1.0
A. aerogenes	10	5-6	10,000,000	3.3
	7	13	3,400,000	< 0.13
Extract of leaves:				
A. aerogenes	10	4	8,300,000	0.2
	5	9-10	3,500,000	< 0.067

* As determined by the standard water measurement technique

While removal of loosely attached organic solids or slimes may be possible by manual wiping, precipitated material will probably require chemical removal. Accordingly, when iron salts are used in wastewater pretreatment prior to UV disinfection, care should be taken to ensure that iron levels remain low in the wastewater at all times.

Until more is known about the factors of wastewater quality that will affect the UV disinfection process, each UV application should be considered as unique. Therefore, bench and pilot-scale studies are advisable at each site.

2.5 Effects of Temperature on Resistance of Organisms to UV

Within the working temperature range for disinfection of wastewater, resistance of organisms is essentially independent of temperature (5). This would be expected since UV inactivation is a photochemical process and photochemical processes are not very temperature sensitive.

2.6 Effects of Dissolved Oxygen

In general, the action of UV appears to be independent of the presence of dissolved oxygen during irradiation. However, the presence or absence of oxygen during cell growth prior to irradiation has a striking influence on UV effectiveness. Investigations (26) by Hodgkins and Alpen (1963) with different strains of E.coli disclosed that aerobically grown cells were more susceptible to UV than anaerobically grown ones. Therefore, in principle, it is desirable to precede UV disinfection by aerobic treatment processes.

3. CHARACTERISTICS OF ULTRAVIOLET EQUIPMENT

3.1 Lamps

There are various sources of UV radiation but low pressure, mercury vapour, arc discharge lamps have been used almost universally for research and disinfection applications. The lamps are simple to use and provide a suitable intensity of radiation. They typically convert 60% of input electrical energy to UV; 90% of total ouput radiation is emitted in the germicidal region of 2537 Å (6). The balance of input energy is converted into heat (38%) and light (2%).

UV lamps and ancillary equipment such as ballasts and relectors show many similarities with conventional fluorescent lamps. The UV lamps differ in not having a phosphor coating on the inside of the bulb and also because the bulbs are of quartz (27).

The major differences between different types of UV lamps are in the electrodes used and the corresponding ballasts needed to match various electrode characteristics. Hot cathode lamps have tungsten filaments coated with an emission material and an electrode preheat circuit. The life expectancy of these lamps is mainly dependent on the life of the filament which is difficult to predict exactly. Premature failures can therefore shorten the life of individual lamps. The applicability of hot cathode bulbs is limited since they have unreliable startup characteristics at low temperatures. However, they require a low starting voltage (118 to 200 volts) and a relatively inexpensive ballast (14).

Cold cathode lamps have cylindrical electrodes which permit instant startup on application of 400 to 750 volts to the electrode. With this design, dependable starting can be obtained even at low temperatures.

Cold cathode lamps need a ballast with a very high open circuit voltage (14). Their electrodes are cylindrical and coated with an emission material similar to that used in hot cathode lamps. Electrodes seldom fail by breakage in these lamps. Therefore, the life expectancy of a cold cathode lamp is more predictable because it is based on a slow decrease in the UV transmission due to other factors.

Operating voltages for hot cathode lamps range from 50 volts to 100 volts while cold cathode lamps have an operating range of 235 volts to 410 volts (14).

Changes in voltage delivered to the UV lamp affect the output of the UV radiation from the lamp. Figure 5 (28) shows the changes which occur in the UV output of the lamp (GEG4T/1) when the line voltage is varied above and below 110 volts. If voltage fluctuations are expected, a fall in UV output with decreased voltage should be allowed for in initial design.

The useful life expectancy of a UV lamp is that time for which it will produce an intensity above a minimum design figure. Germicidal output of a lamp is highest at the time of first use and falls rapidly during the first 100 hours of service. The rapid fall occurs because the electrical arc discharge in the bulb affects the bound water in the quartz envelope which lowers the UV transmission. UV output then declines much more slowly for the life of the lamp. The gradual decline is due to two factors. First, continued passage of electrical energy produces a gradual release of the electrode coating of the lamp which is then

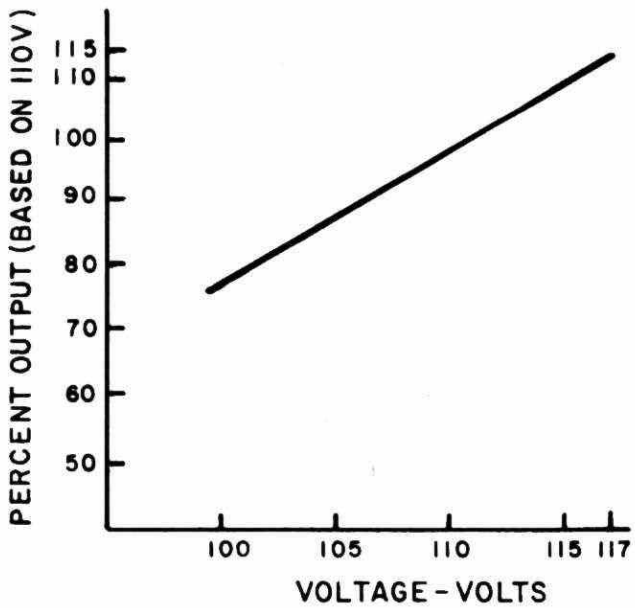


FIGURE 5: PERCENT OF UV OUTPUT WHEN LINE VOLTAGE IS VARIED ABOVE AND BELOW 110 VOLTS (*28*)

deposited on the inside of the quartz bulb. Secondly, the heat, pressure and plasma arc produced by normal operation within the bulb gradually alters impurities in the quartz. Both effects result in a gradual decrease of UV transmission through the bulb and therefore a decrease of the UV output (27).

Immersed lamps (or their quartz sheaths) need periodic cleaning to remove surface buildups. Cleaning may consist only of a manual wiping of the quartz sheath or more involved chemical cleaning using a dilute organic acid such as citric or acetic acid. The length of time that a unit can be operated before cleaning is necessary is not well defined for wastewater applications.

The life expectancy of a lamp is also affected by the mode of operation. For example, one lamp (GEG30T/8) with a rated life of 7500 hours (10 months) under intermittent use, has a rated life of 9000 hours (12 months) in continuous use (2). Sewage disinfection would normally be continuous, year-round or at least seasonally, By contrast, disinfection of combined sewer overflow or stormwater would normally be intermittent - which suggests lamp life would be shorter for these applications than for secondary wastewater.

Germicidal lamps require a warmup time before peak efficiency is reached. Test results (3) indicate that peak UV intensity should be achieved after 2 minutes. Jagger (6), however, has recommended a start-up time of 20 minutes. The longer time may reflect some allowance for lamps to reach full operating temperature with low ambient air or water temperatures.

3.2 Quartz Sheaths

As noted previously, quartz sheaths were originally combined with mercury lamps in 1906 (11). A sheath minimizes the adverse effects of low liquid temperature on lamp startup and operating efficiency by providing an air gap which effectively insulates the lamp against the low temperature. Quartz was selected because it has high transparency to UV wavelengths, a high melting point and a low coefficient of expansion.

The effect of lower lamp operating temperatures upon operating efficiency is illustrated in Figure 6 for a specific lamp (GEG4T4/1). A lamp without a quartz sheath emits about 50% of its output of radiation in the germicidal wavelength range at an operating temperature of $10^{o}C$. With a quartz sheath, UV output increases to about 90%. It should be noted that if the liquid being treated has a temperature consistently above $16.5^{o}C$, then the quartz sheath could not possibly be economically justified based on power savings.

The quartz sheath also has a secondary benefit. Suppliers of submerged lamp units place a watertight seal between each quartz sheath and the liquid. This allows individual lamps to be removed without shutting down a complete UV unit for draining.

3.3 Reflectors

Suspended lamps are used with a reflector mounted above the lamp to direct the maximum amount of light downward towards the liquid surface. Many materials are suitable and Table 4 (29) shows the reflectance of light in the region of germicidal wavelengths for common reflector materials including paints, pigments and whiteners. Aluminum is the material most frequently used since in addition to having a high reflectance, it is light weight, inexpensive and easily fabricated to the shapes required.

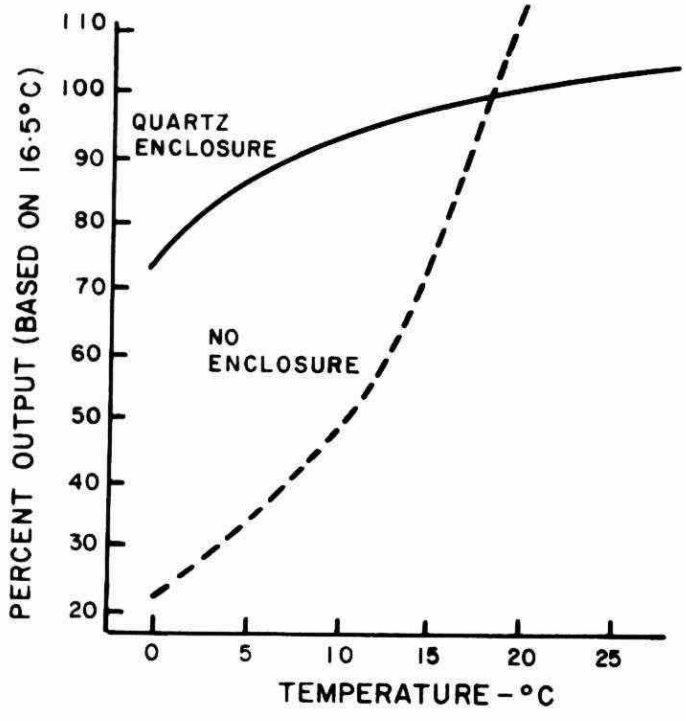


FIGURE 6 : PERCENT OF UV OUTPUT - LAMP IMMERSED IN WATER AND PROVIDED WITH A QUARTZ ENCLOSURE (11)

TABLE 4

REFLECTANCE OF VARIOUS MATERIALS FOR UV LIGHT (29)

Material	*Percentage Reflectance*
Aluminum	
Untreated Surface	*40-60*
Treated Surface	*60-89*
Sputtered-On Glass	*75-85*
Paints	*55-75*
Stainless Steel	*25-30*
Tin Plate	*25-30*
Calcium Carbonate	*70-80*
White Oil Paints	*5-10*
Zinc Oxide Paints	*4-5*

Reflectors are made in a number of different configurations. Figure 7 illustrates the effect of using a cylindrical-parabolic reflector above a UV lamp. This results in significantly increased UV intensity below the lamp as compared to the intensity from a similar lamp without any reflector.

Figure 8 shows how the UV intensity varies spatially through air when using a 30 watt germicidal lamp with aluminum flat wing reflectors at 45^{o}. *The concentration and spatial distribution of the reflected UV light is an important design consideration for suspended lamp units.*

Reflection is not of great importance in units with submerged lamps. However, the internal surfaces of the equipment casing and any internal baffles can be coated with high reflectance material as an aid to better efficiency.

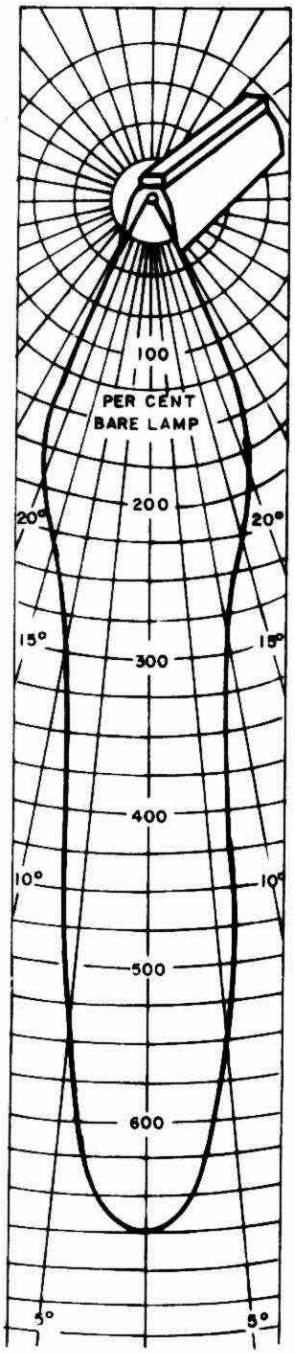


FIGURE 7: SPATIAL DISTRIBUTION OF UV LIGHT INTENSITY FROM A UV LAMP WITH AND WITHOUT A CYLINDRICAL PARABOLIC REFLECTOR (31)

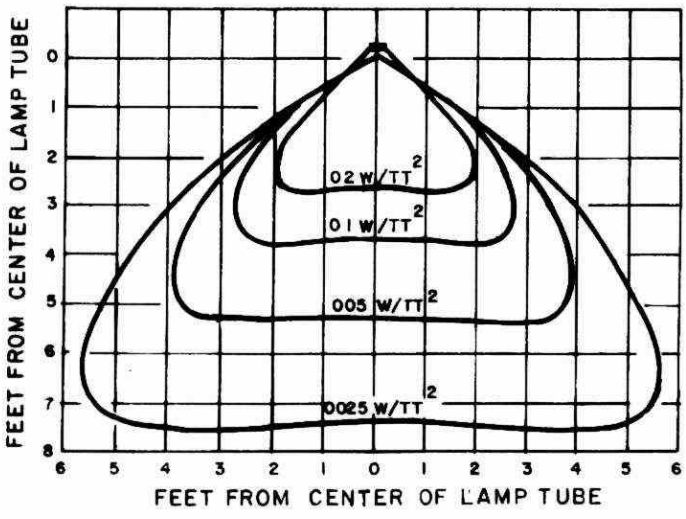


FIGURE 8: ISO – INTENSITY CURVES IN PLANE PERPENDICULAR TO 30 WATT GERMICIDAL LAMP WITH ALUMINUM FLAT WING REFLECTORS AT 45° (31)

3.4 UV Sensors

UV sensors of various types exist and can be supplied either as fixed or portable instruments. On commercial units for water disinfection, they are usually fixed and measure intensity at one point in the equipment. Because of the limitations of single point sensing of intensity, status lights are sometimes provided to give a positive indication that individual lamps are drawing electrical current.

UV sensors are of three basic types. Sensors using photovoltaic cells as the detectors are the least expensive and least selective. These cells measure both UV and visible light (31) and hence true UV intensity is not indicated. It follows that changes in UV intensity may be masked if the detector continues to sense other wavelengths. Filters which selectively transmit UV light are sometimes added to photovoltaic cells to enhance sensor response.

A second type of sensor uses a chemiluminescent detector. These sensors can be manufactured to respond to UV wavelengths only. Therefore, they are not subject to the limitations of accuracy to photovoltaic cells. The chemiluminescent sensors cannot be cosine corrected to compensate for the angle of incidence of the UV light but they do give a direct reading of intensity. These sensors photochemically degrade with the passage of time, and the reliability of the intensity readings declines (31).

The most accurate, and the most expensive sensors are vacuum photodiodes. As an example of this type, the sensor manufactured by Ultra-Violet Products Inc. measures UV light in the germicidal range, uses a silicon photodiode (32) which is cosine corrected and has a rated accuracy of $\pm$2% at the calibrated wavelength. Cosine correction allows for the accurate measurement of the intensity of the UV light irrespective of the angle of incidence of the light (32). The photodiode sensors can be readily connected into alarm and failsafe systems.

While sensors supplied with disinfection units are usually connected to a relative readout dial with gradation in percentage points, the sensor head could also be connected to an appropriate meter to give intensity readings in microwatts/sq cm.

3.5 Equipment Assemblies

Individual UV lamps must be assembled into arrays or assemblies for use at large-scale. Whilst many different equipment configurations have been used, most water and wastewater disinfection units built to date have been of two main types. These can be categorized as "suspended lamp/thin film" equipment and "submerged lamp/thick film" equipment.

In the first category, the UV lamps are suspended above a thin film of liquid flowing through a shallow channel or chamber. There is an air gap between the bottom of the lamps and the liquid surface.

In the design of these units, no "renewal" of the liquid surface by turbulence is allowed for; adequate radiation is assumed to penetrate to the full working depth. A typical depth recommended for wastewater disinfection is 0.5 cm (4).

The lamps suspended over the liquid are normally enclosed in a housing. This confines the radiation to a known area as a basic safety precaution for the benefit of operating personnel. The housing can also be designed to minimize the effects of changes in air temperature and weather on the UV equipment itself. Additionally, housing can provide protection to the equipment against vandalism and accidental damage.

Reflectors are placed above each bulb to ensure the maximum amount of light or energy is directed downwards. While gravity flow-through of liquid is typical, the units may be fed from a headbox to which the flow is pumped. Suspended lamp units of this type require much more floor space to treat a given volume of liquid than do immersed lamp units. References to large-scale disinfection units using the suspended lamp arrangement were not located in the literature survey.

Thick film submerged lamp units have been more widely used than the suspended lamp units - especially for water disinfection. In these units, an outer shell or casing is used to enclose and support the array of UV lamps, which may or may not be enclosed in quartz sheaths. The lamps are fully immersed. Flows may be pumped directly to the units or enter by gravity from a headbox. The lamps can be arranged in any way which satisfies the critical design requirement of obtaining a sufficient level of irradiation for all the liquid by the time it leaves the unit. The liquid flow path may be baffled to promote turbulence and to minimize short-circuiting.

Each type of unit offers relative advantages and disadvantages which are summarized in Table 5. There is insufficient operating experience and relative cost data available at present to clearly favour either type for wastewater disinfection, or to regard these as the only configurations likely to prove suitable.

TABLE 5

RELATIVE ADVANTAGES OF DIFFERENT TYPES OF EQUIPMENT

Submerged Lamp/Thick Film	*Suspended Lamp/Thin Film*
Coating of lamps or quartz sheaths can lower UV transmission.	*Slight coatings of dust and vapour have little effect. Lamp coating should not occur but lamps must be protected from splashing.*
Equipment occupies a minimum of floor space.	*Equipment occupies a large floor space.*
Quartz sheaths are needed to maintain high lamp efficiency at low liquid temperature.	*Air space around the lamps should be kept warm to maintain high lamp efficiency at low ambient air temperature.*

3.6 Flexibility, Reliability and Ease of Operation

In principle, UV units can be fully automated for startup and shutdown. Remote activation of equipment can also be easily arranged. Normal field inspection and routine maintenance can probably be carried out by operators without special skills. There are no chemicals to transport to site and the disinfection facility offers a low level of hazard to the surrounding area and to operating personnel.

The above factors seem to be particularly advantageous for disinfection of stormwater or combined sewer overflows at unattended or remote treatment facilities.

In principle, UV equipment is also capable of flexible and automated operation. However, these abilities have yet to be convincingly demonstrated for wastewater disinfection service. Monitoring of UV intensity, and possibly colour and turbidity, appears advisable.

4. COST OF UV DISINFECTION

The cost of disinfection will be highly dependent on the type and quality of wastewater, incoming bacterial levels and the final bacterial level required. The indicator organism selected also affects the cost - costs developed for inactivation of total coliforms may differ widely from those for virus inactivation.

In developing costs for situations in which a chlorine residual in the receiving stream is unacceptable, UV disinfection is best compared with the total cost of chlorination-dechlorination.

A cost comparison between UV and chlorine disinfection is presented in Table 6. The total cost column includes amortized capital costs and operating costs. The data is for the disinfection of a secondary effluent from a 1 USMGD (3780 m^3/d) treatment plant for a target level of 1000 TC counts/100 mls, and does not include costs for standby or backup equipment.

The data shows that chlorination costs less than UV disinfection. If dechlorination is required, it is claimed that capital and total costs are comparable (16). For larger plants, the UV disinfection process does not benefit as much from economies of scale as does chlorination. The result is that for a 10 USMGD (45,400 m^3/d) plant, chlorination/dechlorination costs about 0.22¢/m^3 (1¢/1000 US gals) less than UV disinfection. In Ontario, roughly half of all secondary treatment plants have a capacity of 1 IMGD or less.

Lamp replacement is the biggest operating cost in UV disinfection accounting for up to three quarters of the total (2). Power conumption accounts for most of the remaining operating cost.

TABLE 6

COST COMPARISON* - CHLORINE AND

ULTRAVIOLET DISINFECTION (16)

	Capital Cost $	Total Cost ¢/m^3
Chlorination	60,000	0.92
Chlorination/Dechlorination by SO_2	71,000	1.16
UV Disinfection	71,000	1.11

* Costs are for a 3780 m^3/day (1 USMGD) plant

5. CONCLUSIONS

1. *UV irradiation by low pressure mercury vapour lamps is capable of adequate and consistent disinfection of contaminated waters, provided that substances which absorb or hinder transmission of the radiation or shield microorganisms are not present above critical concentrations.*

2. *Minimal data are available on UV disinfection of stormwater or combined sewer overflows.*

3. *In principle, UV disinfection appears attractive for terminal disinfection of secondary or higher quality municipal wastewater at smaller treatment plants as an alternative to chlorination-dechlorination. However, process practicality has yet to be proven in full-scale installations.*

4. *Suspended solids, turbidity and colour are among the contaminants known to affect the efficiency and cost of UV disinfection, but the relative importance of each has not been established in wastewaters.*

5. *In general, UV irradiation of water does not induce toxicity to aquatic life. While limited in extent, the data available on UV disinfected secondary wastewater also indicates a lack of induced toxicity.*

6. *UV irradiation of contaminated waters can potentially change the mutation rate of microorganisms and induce chemical changes in organic contaminants. Photoreactivation of microorganisms may also occur in some circumstances. The practical significance of such possible effects has not been well researched in relation to wastewater disinfection.*

REFERENCES

1. *Cairns, V.W., Tonelli, F.A., Netzer, A., "The Acute Lethality of Disinfection Alternatives", Technology Transfer Seminar on Disinfection, B.C. Water and Waste Association and Environmental Protection Service, Harrison, Hot Springs, B.C., April, 1977.*

2. *Oliver, B.G., Carey, J.H., "Ultraviolet Disinfection: An Alternative to Chlorination", Journal Water Pollution Control Federation, 48, 11, 2619, (November, 1976).*

3. *Oliver, B.G., Cosgrove, E.G., "The Disinfection of Sewage Treatment Plant Effluents Using Ultraviolet Light", The Canadian Journal of Chemical Engineering, 53:170-174, (April, 1975).*

4. *Oliver, B.G., Carey, J.H., "A Scale-Up Investigation of Ultraviolet Disinfection as an Alternative to Chlorination for Sewage Effluents", The Canadian Journal of Chemical Engineering, Vol. 53, December, 1975, Pg. 711-712.*

5. *Singer, M., Nash, N., "Ultraviolet Disinfection of a Step Aeration Effluent", New York Water Pollution Control Association, January 18, 1977.*

6. *Jagger, J., "Introduction to Research in Ultraviolet Photobiology", Prentice-Hall Inc., Englewood Cliffs, N.J.*

7. *Loofbourow, J.R., "Effects of Ultraviolet Radiation on Cells' Growth", Vol. 12, 1948, Pgs. 75-149.*

8. *Gurak, R., "Development of a Novel Process for the Treatment of Domestic Sewage", Doctoral Thesis, University of Toronto, 1975.*

9. *Vajdic, A.H., "The Inactivation of Viruses in Water Supplies by Ultraviolet Irradiation", Ontario Water Resources Commission, Division of Research, Paper 2015, June, 1969.*

10. Oda, A., "Ultraviolet Disinfection of Potable Water Supplies", Ontario Water Resources Commission, Division of Research, Paper 2012, March, 1969.

11. Jepson, J.D., "Disinfection of Water Supplies by Ultraviolet Radiation", Water Treatment and Examination, Vol. 22, 1973, Pg. 175.

12. Rokosh, D., Ontario Ministry of the Environment, personal communication, May, 1977.

13. "EPA's Research and Development Report on Wastewater Disinfection", Technology Transfer, U.S. EPA, October, 1977.

14. "Germicidal Ultraviolet Tubes", Westinghouse, Booklet A-8968, June, 1976.

15. Personal Communication, August, 1978.

16. Task Force Report, "Disinfection of Wastewater", U.S. EPA, Office of Research and Development, July, 1975.

17. Zarnett, G.D., "Energy Requirements for Water Treatment Systems", Applied Sciences Section, Ontario Ministry of the Environment, Research Paper No. S2043, April, 1977.

18. Luckiesh, M., Holiday, L.L., "Disinfecting Water by Means of Germicidal Lamps", General Electric Rev. 47, 45, 1944.

19. Support documentation for a UV disinfection unit produced by Aqua Pur Inc., London, Ontario.

20. Setlow, R.B., Pollard, E.C., "Molecular Biophysics", Addison Wesley, 1962, pg. 287.

21. *Kelner, A., "Photoreactivation of Ultraviolet-Irradiated Escherichia Coli, with Special Reference to the Dose-Reduction Principle and to Ultraviolet-Induced Mutation", J. Bact. 58, 1949, pg. 511-522.*

22. *Arnold, E., "Principles of Bacteriology and Immunity", 4th Ed., Vol. 1, Topley & Wilson, London, 1955, pg. 349.*

23. *Waller, D.H., "Introduction", Manual of Practice on Urban Drainage, Draft No. 3, March, 1977.*

24. *Tonelli, F.A., Ho, A.K.W., "Efficiency of Chlorine, Chlorine Dioxide and Ozone as Chemical Disinfectants in Non-Nitrified, Nitrified and Denitrified Wastewaters", EPS Technology Transfer Seminar on Disinfection, September 21, 1977.*

25. *Huff, C.B., Smith, H.F., Boring, W.D., Clarke, N.A., "Study of Ultra-violet Disinfection of Water and Factors in Treatment Efficiency", Public Health Reports, 80, 8, 695.*

26. *Chang-Chih Tai, "Action of 254 nm and 320-400 nm Radiation on Bacteria under Semi-Dried Conditions", Doctoral Thesis, University of Saskatchewan, April, 1971.*

27. *Felgate, G.F., Westinghouse Ltd., Personal Communication, May, 1978.*

28. *Cortelyou, J.R., McWhinnie, M.A., Riddiford, M.S., Semrad, J.E., "The Effects of Ultraviolet Irradiation on Large Populations of Certain Waterborne Bacteria in Motion", Applied Microbiology 2, 5, 269-273, (1954).*

29. *Kaufman, J.E., Christensen, J.F., "I.E.S. Lighting Handbook", 5th ed., Illuminating Engineering Society, New York, New York, 1972, Pgs. 25-1 to 25-2.*

30. *"Germicidal Lamps", General Electric, TP-122.*

31. *Reynolds, C.A., Aquafine Corporation, Personal Communication, May, 1978.*

32. *"Owner's Manual - J-260 Digital Radiometer", Ultraviolet Products Inc., San Gabriel, California, 1977.*

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